

# Evolution of Requirements and Assumptions for Future Exploration Missions

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NASA programs are maturing technologies, systems, and architectures to enabling future exploration missions. To increase fidelity as technologies mature, developers must make assumptions that represent the requirements of a future program. Multiple efforts have begun to define these requirements, including team internal assumptions, planning system integration for early demonstrations, and discussions between international partners planning future collaborations. For many detailed life support system requirements, existing NASA documents set limits of acceptable values, but a future vehicle may be constrained in other ways, and select a limited range of conditions. Other requirements are effectively set by interfaces or operations, and may be different for the same technology depending on whether the hardware is a demonstration system on the International Space Station, or a critical component of a future vehicle. This paper highlights key assumptions representing potential life support requirements and explanations of the driving scenarios, constraints, or other issues that drive them.

## Nomenclature

<i>KDP</i>	=	Key Decision Point
<i>LEO</i>	=	Low Earth Orbit
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>NPR</i>	=	NASA Procedural Requirement
<i>NPD</i>	=	NASA Policy Directive
<i>PDR</i>	=	Preliminary Design Review
<i>SP</i>	=	special publication
<i>SRR</i>	=	System Requirements Review
<i>TRL</i>	=	Technology Readiness Level

## I. Introduction

TECHNOLOGY developers for human spaceflight vehicles are often caught in a frustrating conundrum when trying to develop new systems because mission developers and vehicle owners are unlikely to accept the risk of new technology without sufficient maturity and demonstration. Yet, it is difficult to demonstrate the technical maturity required until the mission requirements, concept of operation, and environment are well defined.

NASA programs and projects are required to follow official directives in documents such as NASA Policy Directives (NPDs), NASA Procedural Requirements (NPRs), and NASA standards with supplementation from NASA special publications (SP). Mission developers are subject to “NASA Space Flight Program and Project Management Requirements” (NPR 7120.5E), which states that the details for executing each phase of a project are found in “Systems Engineering Processes and Requirements” (NPR 7123.1B) and the “NASA Space Flight Program and Project

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Management Handbook” (NASA/SP-2014-3705). This handbook states that upon completing Phase B—the work following a System Requirements Review (SRR) and ending in a Preliminary Design Review (PDR)—that “The project completes mission-critical or enabling technology, as needed, to the level of a system/subsystem model or prototype demonstration in a relevant environment (ground or space) (Technology Readiness Level (TRL) 6 by Key Decision Point (KDP) C) unless otherwise documented in the Technology Development Plan.”<sup>1</sup> A key challenge is that if NASA wants to both perform long missions and move efficiently through development processes for long duration missions may quite likely that the demonstration time necessary to reach TRL 6 will be longer than the period of time between SRR and PDR! Most program managers are not eager to accept the extra risk of delaying technology development. Thus, technology developers need to project forward their best assumptions of what future requirements will be so that development efforts will be relevant to the future program needs which for long duration human exploration missions include reliability and logistics planning which can be difficult to define.

One critical NPR for life support system (LSS) developers is “NASA Health and Medical Requirements for Human Space Exploration” (NPR 8900.1B) which levies “NASA Space Flight Human System Standard Volume 2: Human Factors, Habitability, and Environmental Health (NASA-STD-3001 Vol. 2) as a source of requirements for all NASA human exploration programs. These documents are often described as “tailorable”, and in fact, NASA-STD-3001-Vol 2 states, “Volume 2 of NASA-STD-3001 is applicable to all human space systems. Developers of a system are to write design requirements tailored for their system that will ensure the end product meets the requirements of Volume 2. A supplementary NASA document, NASA/SP-2010-3407, Human Integration Design Handbook (HIDH), can help with the preparation of the system specific design requirements.”<sup>2</sup>

There are, therefore, many sets of requirements that can be set for a future vehicle that would still meet legal constraints and the purposes of these documents. These documents also do not address interface and environment requirements that are derived from technology implementation choices. For example, acceptable limits for microorganisms in potable water is defined, but the choice of a residual biocide or other microbial control method is not specified.

In order to prepare for future exploration missions, technology developers are participating in system and vehicle conceptual design activities for cislunar proving ground missions and Mars vehicle concept studies with the objective of addressing exploration figures of merit that include safety, mission success, effectiveness, and affordability.<sup>3</sup> The concept of operations for these missions helps define the range of needed requirements. For example, frequent or infrequent spacewalks could drive different needs for total pressure and oxygen levels. Trade studies or evolutionary development plans can set interfaces based on other systems, such as assuming reuse of an Orion system like a toilet for a shared logistics chain. NASA also expects that future missions will be performed in partnership with other nations, who may have their own defining documents.

The content that follows documents work in progress, and useful but not officially approved predictions or considerations for the requirements that future LSS designs will need to meet.

## **II. Assumptions from Tailoring or Expecting Changes in NASA Standards**

Consideration must be given to recent developments relating to the need to control the CO<sub>2</sub> partial pressure to levels well below the published 1000-day SMAC of 8990 mg/m<sup>3</sup> (3.8 mm Hg).<sup>4, 5</sup> As recent studies are indicating correlation with the incidence of headaches and chronic cognitive effects associated with CO<sub>2</sub> partial pressures that have been considered to be safe, a growing body of evidence is indicating that controlling to CO<sub>2</sub> concentrations <4730 mg/m<sup>3</sup> (2 mm Hg) may be necessary for future exploration missions if crew health and performance observations aboard the ISS are confirmed by ground-based studies.<sup>6</sup>

Trace contaminant spacecraft maximum allowable concentration (SMAC) standards will need to be adjusted to account for increasing mission durations. Operationally, the International Space Station (ISS) contamination control system designs are based on SMACs for 180-day (NASA) and 365-day (Russia) continuous exposures. While these standards are suitable for cislunar exploration mission LSS design, the exploration end state for Mars exploration will extend to total mission durations that can exceed 1,000 days. While some SMAC standards have been established for some key LSS design-driving trace contaminant compounds, the future vehicle, habitat, and mission environment may lead to identifying emerging compounds of interest that may further drive designs. As well, new information on toxic effects and interactions with the mission environment may require modifications to existing 1,000-day SMAC standards. Therefore updates to the SMAC standards to address missions through Mars exploration will be expected.

Another potential change in humidity requirements comes from comparing a NASA standard with a Russian standard in the “GOST” (ГОСТ for государственный стандарт), which translates as “State Standard”. In the HIDH, the ranges of relative humidity that are acceptable for indefinite periods are >30% – 50% as the nominal range, and >25% – 75% as a tolerable range. The GOST standards request relative humidity in a band of 30%-70% relative humidity.

In discussions with experts, an opinion is sometimes issued that higher humidity is more comfortable to crew. Though experts in both Russian and US systems agree that comfort is a mix of both temperature and relative humidity, and also activity level. The HIDH rationale for the range states that “Low humidity causes drying of the eyes, skin, and mucous membranes of the nose and throat, which can lead to an increased incidence of respiratory infections (Carleon, 1971). High relative humidity can result in condensation on surfaces, which can be conducive to microbial and fungal growth. Water vapor pressure of 0.19 psi (10 mmHg) is optimal for habitability.” Microbial and fungal growth is a serious concern in closed spacecraft environment, but the vehicles ability to control condensation depends both on the internal humidity and on the ability to control wall and other surface temperatures. The “optimal” water vapor pressure results in a dewpoint of 52F (11C), and a relative humidity of ~50%. Given a control band of 30%-50%, a life support designer is unlikely to pick a set point at the maximum value in the band. With all of these considerations, it seems reasonable to set a requirements range for future vehicles in an international partnership with nominal relative humidity from 30% to 70%, and an expectation of operation near or above 50% relative humidity. This would be levied in parallel with a requirement to avoid condensation.

This range and set of operational constraints related to wall temperature is likely to have two impacts on life support designs. Passive thermal systems must do a very good job of controlling wall and surface temperature, either through waste heat use, or heaters. Extra power for heaters is not desirable, but some vehicle concepts have large solar arrays for propulsion and this capacity would be small in comparison. If wall temperatures are going to drop because of an environment change or power availability change, the life support system must be prepared with surge capacity to reduce the cabin dewpoint. Also, it is possible that staged series heat exchangers different heat rejection temperatures and different bypass control could be necessary to more independently control sensible and latent heat removal, since US vehicles have historically had low relative humidities.

### **III. Cislunar Concept of Operations Derived Requirements**

NASA intends to use missions in and around the Earth-Moon system to prove technologies, vehicle designs, and operations tools that will be needed for Mars exploration missions. But these missions won't immediately be excuted as Mars mission simulations, so the life support system design may initially have unique constraints or requirements added to the system.

#### *1. Dormancy*

One of the first and most obvious considerations is dormancy. NASA's recent history has two very successful human spaceflight programs, but neither is a good analog for the operational cadence of cislunar missions. The Orbiter vehicles in the Space Shuttle Program were returned to Earth and very carefully refurbished before their next mission. The ISS program began with Russian modules and relatively passive NASA modules. The NASA life support systems, especially the closed-loop recycling life support components, have had continuous human tending. NASA modules were typically delivered and installed by human crews as part of Shuttle missions. In cislunar missions, there will be an incremental build up of capabilities. But while the Orion vehicle surpasses the Shuttle with an ability to venture beyond Low Earth Orbit (LEO) to perform cislunar missions, it does not have the ability to deliver large quantities of cargo. Some components may be co-manifested with Orion on powerful launch vehicles, small components may be launched independently on smaller class launch vehicles, but the largest prototypes of Mars habitats would need to have a dedicated launch.

The result of all of these separate launches is that modules may have long periods of dormancy between the Orion missions that visit them (likely on an annual basis). As capabilities increase, the new modules will add more and more to the Orion capacity, and extend the portion of the year with crew present, and shorten the dormancy. Thus, the earliest modules, expected to have open-loop life support to supplement Orion, should be designed for almost year long dormancy between crew missions. This will effect potable water delivery systems, wastewater collection systems (toilets, condensing heat exchangers). If equipment sizes can be sufficiently minimized, these would benefit from early deployment of closed-loop life support. Using NASA reference architectures, water processing is usually the first part of a closed-loop life support system required. Thus, developers of water processor systems especially should consider how long dormancies would be accommodated in the system. For robust designs, system designers should consider the possibility of “skip cycles”, or a year where a regularly planned launch of crew cannot occur for some reason. This would drive two-year dormancy in the early systems, and year-long dormancy even in fully closed-loop systems. These dormancy constraints are adding excessive cost or requirements to the system because of the cislunar concept of operations, because future Mars missions will have even more difficult dormancy challenges.

## 2. *Depressurization Emergency*

Moving from technology design to system design introduces new requirements from a range of emergency situations. Depressurizations and fire or toxic release are two of the most important drivers for life support systems. Current concepts for handling depressurization are substantially different from either Orion or ISS solutions, while fire solutions benefit from experience and development work from both programs.

When considering depressurization, the cislunar vehicle can be considered as the Orion capsule plus another pressurized volume that is larger than Orion, but significantly smaller than the ISS. The cislunar activities will occur in orbits that have multi-day transit times back to Earth. Depending on location, these times may be longer than 6-days, which is currently Orion's maximum capacity for sustaining crewmembers in their spacesuits in an unpressurized cabin. The Orion vehicle is also designed to have a "Feed the Leak" capability that maintains cabin pressures at a minimum of 8 psia (56 kPa) so that the crew has at least an hour to don spacesuits and connect to the vehicle life support system. If the cislunar pressurized volume begins to leak, the pressure control system will still be trying to maintain nominal pressures of 14.7 psia (101 kPa). If the leak is small and not obvious, a change in use of consumables may be the way in which a problem is detected.

One of the most critical steps in the process will be determining whether the leak is in Orion, or whether it is in the other pressurized elements. This is not a trivial process, and the higher the cabin pressure, the faster gas will be lost from the vehicle. The consumable use rate would be substantially slowed if the vehicle could be allowed to drift to a lower pressure and maintained at a new set point while the leak is located. If the leak is not in Orion, the crew should gather extra consumables like food, bags of stored water, and disposable components for the toilet, and shelter in Orion until a favorable orbital location for return to Earth.

If the leak is in Orion, the situation is more complicated. If the current location is more than 6 days from Earth, the crew will need to make sure that spacesuits and all necessary components are taken out of Orion, and the hatch is closed, and allow Orion to depressurize. After waiting for a favorable orbital location, the crew will need to don their spacesuits and enter the depressurized Orion cabin. But this is effectively an "EVA" (extravehicular activity), performed in the launch and entry suits that do not have Portable Life Support Systems (PLSSs). Adding a "suit loop" configuration life support system to the cislunar vehicle would be a large burden, but the suits could be operated in an open loop "purge" mode with oxygen supply. Also, the module docked to Orion must be depressurized so that the hatch can be open for crew transfer. The crew will need to perform oxygen prebreathe somehow, likely in their spacesuits venting gas, and the cabin is depressurized. If the cabin has been maintained at a lower pressure during the wait, the prebreathe duration will be shortened. If the suit is in an open-loop purge, this must be maintained until the cislunar vehicle depressurizes so crew transfer can be completed. This will be faster if the cabin starts at a lower pressure. Thus, this scenario will be easier to manage if the cislunar vehicle is designed for lower pressures and higher oxygen concentrations.

The Exploration Atmospheres Working Group (EAWG) recommended a range of control points with decreasing total pressure and increasing oxygen concentration for various purposes. The cislunar vehicles are expected to nominally operate at the 14.7 psia (101 kPa) 21% O<sub>2</sub> control point. The lowest control point recommended by EAWG was 8.2 psia (56 kPa) and designing for up to 34% O<sub>2</sub>. While this would only be a nominal set point for vehicles with very high frequency EVA, designing the vehicle to accommodate this point would greatly increase options in emergency situations. Additionally, components and crew equipment in the vehicle designed for these points would then be extensible to the future exploration vehicles that would use lower pressures as nominal set points. At minimum, something like the 10.2 psia (70 kPa) and 26% O<sub>2</sub> atmospheres (used for "EVA Campout" operations on ISS to reduce prebreathe time) is probably necessary to enable the EVA transfer with reasonable prebreathe and reasonable decompression sickness risk. A reasonable intermediate point that might be considered is the Orion requirements for a minimum pressure set point of 9.5 psia (65 kPa) (not including vacuum contingencies), and a selectable partial pressure of oxygen from 2.7 to 3.1 psia (19 to 21 kPa). The worst case combination of these set points would be 32% oxygen, though control bands could allow it to drift farther so the 34% EAWG oxygen concentration is applicable.

## 3. *Fire Emergency*

The ISS has unique emergency systems depending on whether the module was provided by the US or Russia. Dissimilar redundancy from the partners has been useful in some cases, such as CO<sub>2</sub> removal and oxygen generation. But it would be useful for future vehicles to have a consistent emergency system to simplify crew training and the speed of crew response, since it would be consistent regardless of where the emergency occurred. On the ISS, each side has different types of fire extinguishers. Russian water fire extinguishers were not compatible with the higher voltage systems on the US side. The kind of fire extinguisher also drives the kind of emergency mask the crew will wear while fighting the fire. Some extinguishing agents, such as Halon used on the Space Shuttle, are not compatible

with certain kinds of life support systems, like the ISS high temperature trace contaminant removal system. Others, like CO<sub>2</sub> or water can be removed from the atmosphere by existing life support system components.

The Orion spacecraft design includes a new water mist fire extinguisher. This new technology uses droplets fine enough that they are safe to use with higher voltage electronics without creating a conductive shock path. Standardization efforts for power systems in cislunar vehicles are driving toward having higher voltage distribution systems, but this would be safe to use with those systems. It would also be non-toxic, easy to remove after the fire, allowing many options for personal protective equipment and post-fire cleanup responses.

#### **IV. Mars Mission Concept of Operations Derived Requirements**

Exploration missions to Mars may vary in duration for both the round trip transit and surface operations phases. The durations for these phases are influenced by the relative proximity of Earth and Mars. The round trip transit duration can range between 400 days and 650 days for opposition-class missions and 360 days and 420 days for conjunction-class missions. The surface exploration duration for an opposition-class mission ranges between 30 days and 90 days which is much shorter for the 475 days to 540 days for conjunction-class mission surface exploration. In total, an opposition-class mission duration may range between ~500 days to ~630 days and a conjunction-class mission duration may range between ~830 days to ~960 days.<sup>7,8</sup>

The total mission duration and the surface exploration duration present challenges for LSS equipment shelf life as well as for the need to accommodate quiescent or dormant periods for the LSS aboard the transit vehicle and in the surface exploration habitats and rover vehicles. Spare parts and redundant systems will need to have sufficient shelf and operational lives to accommodate missions approaching three years in duration. As well, some of these parts and systems may be used for multiple missions requiring quite long shelf lives and operational periods. The effects of a dormant state of well over a year must be understood to ensure that the LSS can be maintained and restarted safely and reliably after long dormant periods. The most challenging vehicle is likely to be the Mars Ascent Vehicle (MAV). In current mission concepts, the MAV would be launched before the crew for a slow cargo transit to Mars, and spend several hundred days on the Mars surface receiving fuel generated in-situ. Once the MAV is fueled and a return trip is possible, the crew would transit to Mars, and the MAV would stay dormant while the crew transits and during their long surface mission before finally being used.

For the surface exploration phase, the LSS design must consider surface dust intrusion into the surface habitat during the course of EVA and other surface exploration activities. The present surface dust requirements are based on lunar regolith and stipulate that suspended surface dust <10 µm must be maintained below 0.3 mg/m<sup>3</sup> for episodic exposures over a 6-month period.<sup>9</sup> While the lunar dust basis provides a helpful reference for Martian dust, additional assessment of the chemistry of Martian dust relative to its chromium, perchlorate, and manganese content may require a change in the dust concentration standard. Using the experience gained from Apollo and accounting for settling in the low Martian gravity, an estimated surface dust load for this size range is ~15.9 grams/EVA crewmember which increases the basic particulate matter load that the LSS must accommodate by approximately a factor of seven. This intrusion rate, however, is considered to be a worst case and requires further study and will be influenced by future surface habitat dust intrusion barrier designs.

#### **V. Life Support System Interfaces**

The functional and physical interfaces that exist between a crewed spacecraft and the LSS are numerous and can be quite complex. These interfaces account for interactions between the LSS and the crew as well as the vehicle's structural, command and data handling (C&DH), electrical power, thermal control, logistics management, and EVA systems. Technology choices and lessons learned from previous long-term spacecraft LSS operations such as Mir and the International Space Station (ISS) can provide insight for better understanding and improving functional and physical interfaces to realize gains in functional efficiency and reliability. For the LSS can also Specialty engineering considerations can drive requirements for acoustic noise, materials and processes, and maintainability among other specialty areas. Identifying all of the interfaces an LSS may have requires iteration and a high degree of communication across multiple technical disciplines. These iterative communications to define requirements is challenging and time consuming. Figure 2 represents a preliminary effort to evaluate primary interfaces.

##### **A. Interfaces from the Atmosphere Revitalization Architecture**

The atmosphere revitalization (AR) subsystem must handle crewmembers' daily loads of H<sub>2</sub>O and CO<sub>2</sub> while satisfying their demand for O<sub>2</sub>. For varying mission durations the daily variation and range for these loads and demands

associated with various crew activities, particularly mission-unique exercise countermeasure protocols, must be accommodated. The design must be sufficiently robust to maintain the cabin conditions within specifications despite daily variation in the metabolic loads and demands. The CO<sub>2</sub> control challenge may be enhanced for exploration missions if, as discussed earlier, the partial pressure limit is reduced.

Not only must the AR provide for the crew's normal daily O<sub>2</sub> demand, but also provide for a high purity O<sub>2</sub> product to support medical needs and EVA operations. Requirements and unique interfaces within the AR architecture to supply medical O<sub>2</sub> and to pressurize tanks to pressures up to 24.8 MPa is required. Dependent on the use, the O<sub>2</sub> purity may range between 99.5% and 99.989%.

The AR subsystem architecture receives H<sub>2</sub>O from the potable supply to produce O<sub>2</sub>. As the exploration mission objectives move from cislunar space to Mars vicinity and surface exploration, the need to reduce the mission's water demand via recovering O<sub>2</sub> from CO<sub>2</sub> becomes increasingly important. While the ~52% recovery achieved by the ISS AR subsystem may suffice for cislunar exploration mission, Mars transit missions have the goal to recovery >75% of the O<sub>2</sub> from CO<sub>2</sub>. Mars surface exploration has a goal to achieve >90% O<sub>2</sub> recovery from CO<sub>2</sub>. By employing a resource recovery technology, H<sub>2</sub>O can be returned to the vehicle to minimize the net mission H<sub>2</sub>O demand. Resource recovery technologies can also minimize overboard venting losses. The goals for the long duration transit phase is to recovery >75% of the O<sub>2</sub> from CO<sub>2</sub>. A more challenging goal to reach >90% applies to surface exploration mission phases. Resource losses due to venting must be reduced to <10%.

Operational experience obtained from the ISS has shown that minor trace contaminant species such as formaldehyde, polar organic solvents, thermal control fluids, and volatile methyl siloxanes can emanate from highly diverse, pervasive sources. If these sources are used widely in the vehicle's or habitat's construction, systems, or operations, then they can become a significant design and operational challenge for the AR and other LSS subsystems. For this reason, the materials and processes requirements of the vehicle and LSS design must ensure compatibility between all materials, chemicals, and processes used aboard and the LSS.

Other design experience gained aboard the ISS has shown that cabin major and trace constituents can also diffuse through elastomeric flex hose materials and cause problems with internal fluid composition. For example, CO<sub>2</sub> permeation through Teflon<sup>TM</sup> hose used in the ISS internal thermal control system caused changes in the fluid's chemistry over time that resulted in increased corrosion rates in some thermal control system components as well as increased the fluid's susceptibility to microbial contamination. Also, moisture permeation through hose materials can impact processes that must remain dry. An example is atmospheric moisture permeating through hose materials into dry CO<sub>2</sub> as it is fed to a downstream reduction process. Oxygen and moisture can also readily dissolve in some fluorocarbon thermal working fluids make permeation from the cabin environment an issue. Derived requirements for the AR and LSS that consider gas permeation mechanisms as well as compatibility with the cabin environment are necessary to realize a robust AR and LSS design.

## **B. Interfaces from the Water Recovery Architecture**

The ISS has provided many lessons on potable water management. Having dissimilar providers is useful, since water is critical and many vehicles can provide it. However, having different and incompatible biocides (silver and iodine) on the Russian and US systems has been problematic. Iodine is a long lasting residual biocide, and beds of iodinated material make effective "microbial check valves" allowing water flow but preventing backflow of bacteria. However, the iodine must be removed before the crew consumes the water. This leaves sections of the system unprotected. Silver can be consumed by humans at biocidal levels, but will have compatibility issues with metallic systems that must be considered. NASA intends to move toward a silver biocide system to maximize compatibility with partners systems. But storage and distribution systems will need to be redesigned. The Orion system will be using water treated with silver, and will be one of the first vehicles establishing precedence in exploration vehicles for cislunar and Mars missions. Other biocidal agents are still possible if new technology is developed, but they must be compatible with potable water that contains silver residual biocide.

Potable water quality is likely to remain very similar to standards for previous systems. NASA potable water standards are stricter than general public health standards, since contaminants cannot be assessed on-orbit in existing systems. Some relaxation of contaminants may be possible based on experience and confidence with spacecraft systems. For microbial control, the intent for the cleanliness of the water will likely remain the same. But changes from plate counts for microbial control to other sensors, such as analysis based on cell DNA or RNA, may change the way specifications are written.

### C. Interfaces from the Waste Management Architecture

The same logic that drives standardization of residual biocide will also drive standardization of elements of the waste management system, since wastes like urine or trash could be important resources for these future missions. Originally, both Waste Collection Systems (WCS) on the ISS were provided with a Russian design and utilized a sulfuric acid-chromium urine pretreatment. NASA has transitioned to a phosphoric acid-chromium urine pretreatment to be able to recovery more water from urine in the distillation based urine processor. This pretreatment is still quite toxic, and NASA is still searching for an effective alternative that is compatible with the urine processor. Other international partners, such as JAXA, are examining new water processors and other biocide formulations but these may not be compatible with existing systems.. Technology development is not mature enough to draw conclusions about the best urine pretreatment and water processor for future missions. In fact, dissimilar redundancy from different partners could prove useful in a future mission. But for robust system design, all similar WCS products should be processable by all available processors.

## VI. Conclusions

Technology development, mission operations concepts, and evolving research are all providing insights that will drive changes in the requirements for future life support systems. While the programs that fund and control cislunar and Mars missions may not exist yet, life support technology and system developers can still make informed predictions to drive future designs.

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